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IDENTIFYING AND QUANTIFYING RESISTIVITY ANISOTROPY IN VERTICAL BOREHOLES

T. Hagiwara and H. Zea, Halliburton Energy Services

ABSTRACT

Resistivity anisotropy is not uncommon in earth formations, and the knowledge of its presence and degree can be valuable in petrophysical analysis, well planning, and rig-site safety. The knowledge gathered in vertical wells is important for identifying and evaluating thinly laminated formations, establishing reliable well-to-well correlations when some of the wells are highly deviated, estimating geopressures in deviated boreholes, and geosteering during drilling. Although resistivity anisotropy is readily observable and quantifiable with 2-MHz, logging-while-drilling (LWD), resistivity devices in highly deviated wells, its detection and assessment in vertical holes has been elusive until recently.

A method has been developed to identify and estimate resistivity anisotropy in vertical holes. The method is derived from two-dimensional (2D) modeling of electric- and induction-log responses. From the difference between electric- and induction-log resistivity measurements or between deep- and shallow-investigating, electric resistivity measurements, resistivity anisotropy can be estimated. The method is especially useful when it employs data from a high-resolution induction device and a shallow, focused-resistivity tool, which form a routinely run logging combination.

This paper describes the new method, presents logging data that illustrate its application and support its results, and discusses its application to invaded formations.

INTRODUCTION

Electric resistivity logs often read differently from induction logs in apparently homogeneous formations. Thick shale formations are good examples of such homogeneous formations. In thick shale formations, spherically focused logs (SFLs) and digitally focused logs (DFLs) always show higher resistivity values than dual-induction logs (DILs). In thick shale formations, dual laterologs (DLLs) show higher resistivity than induction logs whenever both types of resistivity logs are run. It has been also noted that deep and shallow laterolog (LLD and LLS) measurements are not equal to each other, as they should be in thick shale formations where no invasion of borehole mud is expected. Deep and medium induction logs (ILDs and ILMs) show identical resistivity values in these formations, indicating no invasion.

Chemali et al. (1987) examined the effect of formation anisotropy on resistivity responses of both laterologs and induction logs with 2D-model calculations and noted that the formation anisotropy causes laterologs to read differently from induction logs. Most significantly, anisotropy affects laterolog responses even in vertical holes. By analyzing the results of Chemali et al., Hagiwara (1994) noted that the effect depends logarithmically on the anisotropy. He then derived a set of empirical equations to relate the difference between laterolog and induction log resistivity to anisotropy. The analysis was extended to include DFLs (Hagiwara, 1997), which are routinely run with high-resolution induction (HRI) logs.

Resistivity anisotropy is not uncommon in formation logging and evaluation. Shale formations are known to be often anisotropic (Clark, 1996; Jackson and Hagiwara, 1995). If a formation has underlying anisotropic geometry, such as aligned fractures and laminations, the formation appears as macroscopically anisotropic to logging tools. For instance, thinly laminated sand and shale sequences exhibit anisotropy (Hagiwara, 1994, 1995). The resistivity in the direction perpendicular to lamination is different from that in the direction parallel to lamination. When coarse- and fine-grain sands form alternate layers in a formation, the formation also exhibits anisotropy because of the layered structure (Klein et al., 1995). The anisotropy effect appears only at higher relative (effective) dip angles (Bittar et al., 1991; Hagiwara 1994, 1995; and Rosthal 1990), namely in highly dipping formations or in highly deviated boreholes, for induction logs and 2-MHz LWD resistivity devices. When the relative dip angle is small, these resistivity tools do not give indications of anisotropy. They measure only the horizontal resitivity in such cases.

Knowledge of whether a formation is anisotropic bears significantly on identifying and evaluating thinly laminated formations (Hagiwara, 1994, 1995). Shale

anisotropy (Jackson and Hagiwara, 1995) is also useful in well-to-well correlations, especially when some wells are highly deviated. To correctly estimate geopressure from shale resistivity in deviated boreholes, shale anisotropy must be known. Anisotropy is also important in geosteering with resistivity data (Jackson et al., 1995; MacCullum et al., 1998; Rosato and Beck, 1997; and Wu et al., 1996). Hence, obtaining anisotropy data in vertical wells is especially useful before field development in areas where highly deviated boreholes or horizontal wells may be drilled later.

One method to identify and estimate anisotropy in vertical wells is to use the differences between electric and induction log resistivities and between deep and shallow electric log measurements. We present the results of 2D model calculations for electric resistivity measurement in vertical holes in anisotropic formations. The results were compared with the actual field data from an assortment of resistivity logging tools, including DFL, HRI, and new hostile-environment dual laterolog (HEDL) tools. Self-consistency among electric and induction resistivity measurements was established after formation anisotropy was considered. From observation, we derived an interpretation method to estimate formation anisotropy either from comparison of electric and induction resistivity measurements or from the difference between deep and shallow electric resistivity measurements. Particularly appropriate is the use of the resistivity data from a shallow-reading, electric resistivity device, such as the DFL that is run routinely run with the HRI tool.

ELECTRIC LOG RESPONSE TO ANISOTROPY

We modeled laterolog responses to anisotropic formations with a 2D modeling code. **Figure 1** shows the effect of formation anisotropy for deep and shallow DLL measurements (LLD and LLS, respectively) and DFL in an 8-inch borehole. **Figure 2** shows how the anisotropy effect changes as a function of borehole size when DLL tool diameter is 3.5 inches and formation anisotropy (R_v/R_h) is 9. R_v and R_h are respectively the vertical and horizontal resistivities of the formation. Note that the effect of anisotropy increases sharply as the borehole size increases from 3.5 to 4 inches, especially at higher (horizontal) formation resistivity. Note also that the effect decreases slowly as the borehole size increases from 6 to 16 inches.

The effect shown in Figures 1 and 2 is a combination of both borehole and formation anisotropy. To estimate the net anisotropy effect, we compared the apparent resistivity in an anisotropic formation (R_a), where $R_v \neq R_h$, with the apparent resistivity in an isotropic formation ($R_{a,isotropic}$), where $R_v = R_h$. The result is shown in **Figure 3**, in which $R_a/R_{a,isotropic}$ is plotted on the y-axis and R_v/R_m on the x-axis. R_m is mud resistivity. We note again that the net anisotropy effect increases sharply as the borehole size increases from 3.5 to 4 inches. In a more realistic situation in which the borehole size ranges between 8 and 12 inches, the net anisotropy increases slowly as borehole size increases. We computed the net anisotropy effect also by applying a borehole correction, assuming an isotropic formation. The borehole-corrected apparent resistivity (R_{ac}) is then compared with induction-log deep resistivity (R_{ILD}), which is the horizontal resistivity R_h. The results are shown in **Figure 4** for different anisotropy values. Note also that the electric resistivity logs always register larger apparent resistivity than induction logs in a homogeneous, anisotropic formation.

In the field, when one tries to detect the anisotropy of thinly laminated sequences, R_v/R_m is usually in a range from 1 to 100, and the net anisotropy effect remains nearly constant. According to Figure 4, the anisotropy effect increases logarithmically in terms of anisotropy R_v/R_h. For an 8-inch-diameter borehole, we (Hagiwara, 1994, 1997) found that

$$R_{ac}/R_h \approx 1.00 + 0.10\, ln\,(R_v/R_h) \text{ for LLD} \qquad (1)$$

$$R_{ac}/R_h \approx 1.00 + 0.17\, ln\,(R_v/R_h) \text{ for LLS} \qquad (2)$$

$$R_{ac}/R_h \approx 1.00 + 0.17\, ln\,(R_v/R_h) \text{ for DFL} \qquad (3)$$

Note that the effect is larger on the LLS than on the LLD. The effect on the DFL is similar to that on the LLS.

The anisotropy effect is relatively insensitive to the borehole size. If, for each tool, we parameterize the above relation as a function of borehole diameter (A_{bh}), we have

$$R_{ac}/R_h \approx 1.00 + b(A_{bh})\, ln\,(R_v/R_h) \qquad (4)$$

The tool-related coefficient $b(A_{bh})$ is nearly constant for A_{bh} between 8 and 16 inches for the DFL, LLD, and LLS. See **Table 1**.

A similar anisotropy effect is observed in other electric resistivity tools. A new dual laterolog tool (HEDL) has been designed for hostile environments. Because HEDL electrode specifications are different from those of the conventional DLL, the effect of

borehole and formation anisotropy on the HEDL response can be different. We found that the anisotropy effect on the HEDL is similar to that on the DLL. Again, the effect is larger on the HEDL shallow resistivity (HLLS) than on the HEDL deep resistivity (HLLD). Modeling analysis suggests that for an 8-inch-diameter borehole,

$$R_a/R_h \approx 1.00 + 0.11\, ln\, (R_v/R_h) \text{ for HLLD} \; \ldots\ldots\ldots (5)$$

$$R_a/R_h \approx 1.00 + 0.16\, ln\, (R_v/R_h) \text{ for HLLS} \; \ldots\ldots\ldots (6)$$

ANISOTROPY DETERMINATION BY ELECTRIC AND INDUCTION LOG COMPARISON

The preceding discussion shows that electric log response is affected by formation anisotropy, even in vertical boreholes, and the anisotropy effect is nearly constant over a wide resistivity R_t/R_m range. On the other hand, an induction log is affected by anisotropy only for high relative dip angles. Induction logs measure horizontal resistivity R_h in vertical boreholes. Therefore, by comparing the electric and induction log resistivities, we can identify and measure the anisotropy of a formation in vertical boreholes.

The preceding empirical relations observed can be used to estimate the magnitude of anisotropy. Note, however, that, because of the logarithmic $ln\,(R_v/R_h)$ dependence, R_v/R_h estimates are sensitive to an R_a/R_h estimate. A 1% change in R_a or R_h would cause nearly a 6.6% change in the R_v/R_h estimate at $R_v/R_h = 9$.

The electric log in this method is not limited to the DLL. For example, the DFL, which has a shallow depth of investigation, is also suitable. Running both a laterolog and induction log is also useful not only for anisotropy detection but also for other aspects of formation evaluation (Mezzatesta et al., 1995). Although running both of these types of resistivity logs in one well or even in an entire reservoir is not a common practice, the HRI is routinely run with a shallow-reading, electric resistivity log, such as a DFL. The data from this combination of logging tools can be used to determine anisotropy if the invasion effect is known or absent. With this combination, the anisotropy of the shallow, invaded area around the borehole is obtained.

ANISOTROPY DETERMINATION BY DEEP AND SHALLOW LATEROLOG COMPARISON

The preceding method requires both induction and electric resistivity logs. As mentioned earlier, running both types of resistivity logs in the same well or even in the same reservoir is unlikely. However, another method is available to detect and measure anisotropy from electric resistivity measurements alone. Namely, if all other environmental effects, particularly invasion, are either absent or corrected, the difference between the LLD and LLS measurements can be used to estimate both R_h and R_v.

Anisotropy R_v/R_h is computed from LLD and LLS resistivity data (R_{LLD} and R_{LLS}, respectively) by

$$R_{LLD}/R_{LLS} = \{1 + b_{LLD}\, ln\, (R_v/R_h)\}/\{1 + b_{LLS}\, ln\, (R_v/R_h)\} \ldots\ldots\ldots (7)$$

or

$$ln\, (R_v/R_h) = (R_{LLS} - R_{LLD})/(b_{LLS}R_{LLD} - b_{LLD}R_{LLS}) \ldots\ldots\ldots (8)$$

Horizontal resistivity R_h is determined by substituting R_v/R_h into Equations 1 through 6.

Figure 5 shows how anisotropy R_v/R_h is estimated from resistivity ratios R_{LLS}/R_{ILD}, R_{LLD}/R_{ILD}, and R_{LLS}/R_{LLD}. Note that the R_v/R_h estimate is sensitive to the R_{LLS}/R_{LLD} ratio, which is closer to 1 than R_{DFL}/R_{ILD}. The anisotropy estimate from this method may be used only qualitatively. The method here is not limited to the DLL data. Data from any two electric resistivity tools can be used as long as the b coefficients for the two tools are sufficiently different from each other.

ANISOTROPY AND INVASION

Without invasion, the different depths of investigation among different resistivity devices hardly matters. Hence, the shallow-investigating DFL data can be compared with ILD and ILM data. The HRI-DFL combination is useful for determining anisotropy in vertical holes in shale formations without invasion and in some laminated formations where invasion is negligible.

When invasion is present, the resistivity data used in the method must be measured at a similar depth of investigation. We may use both DLL and DIL. Both have similar depths of investigation. If ILDs and ILMs show the same resistivity, invasion is negligible, and the ILD resistivity can be identified as the true, horizontal resistivity. We can compare the DLL resistivity to the induction log resitivity. If the ILD and ILM read differently, then at least five resistivity measurements are necessary from the DIL and DLL to determine five unknowns: R_v and R_h in the virgin formation, R_v and R_h in the invaded zone, and the invasion radius.

Alternatively, the shallow-investigating DFL resistivity can be compared with a shallow-investigating induction measurement from any array induction device. The anisotropy obtained from the comparison is the anisotropy of the invaded zone, which is not the same as that of the virgin formation. Nevertheless, the determination that an invaded formation is anisotropic generally implies that the formation is anisotropic because the resistivity anisotropy is a reflection of anisotropy in the geometry of the formation.

FIELD EXAMPLE

The method was applied to actual field data from a thick shale formation in a test well in Fort Worth, Texas. Three types of resistivity logging tools were run in the well: HEDL, DFL, and HRI. The DFL was run simultaneously with the HRI.

The test well is shallow with an openhole section between 1,200 and 1,900 feet. The borehole has diameter is 8 inches and is filled with fresh water. The HRI deep and medium induction measurements (HRD and HRM) show identical resistivity in thick formations. Without invasion, any difference between the deep and medium resistivity readings is attributed to thin-bed effects. The same can be said for the HEDL deep and shallow electric resistivity measurements (HLLD and HLLS). Figure 6a shows the resistivity data from an HRI-DFL combination for the depth interval between 1,500 and 1,700 feet. The gamma-ray (GR) data indicate that the zone between 1,536 and 1,574 feet is shale. The resistivity data for the formation is shown on a linear scale in Figure 6b. Throughout the formation, the DFL resistivity is consistently higher than the HRI resistivity. As expected, both HRD and HRM show the same resistivity values in the shale.

An induction log in vertical holes measures horizontal resistivity (R_h). The difference between HRI and DFL resistivities is used to estimate shale anisotropy. In particular, if $R_{DFL}/R_{HRD} \approx R_v/R_h$, then Equation 3 becomes

$$R_{DFL}/R_{HRD} \approx 1.00 + 0.17 \ln (R_v/R_h) \qquad (9)$$

Although Equation 3 was derived for resistivity data in thick homogeneous formations, we applied Equation 8 to the log data at each depth. The anisotropy thus calculated is nearly constant at about $R_v/R_h = 3.5$ to 4 in the shale formation. See Figure 6c. We do not have any shale resistivity measurement from the core to confirm the anisotropy estimate, but the value is in the range of that observed for shale anisotropy (Clark, 1966).

Laterolog resistivity is affected by anisotropy. Figure 7a shows the comparison between HEDL and HRI log data in the same interval. Unlike HRI deep and medium measurements, HEDL deep and shallow measurements exhibit differences between each other below 1,550 feet, and both are different from the HRI resistivity throughout the shale formation. If the formation is anisotropic and its anisotropy is to be determined from HRI-DFL measurements, then these differences must be consistent. With the assumption that $R_{HRD} \approx R_h$, Equations 1 and 2 can be used to calculate the expected HLLD and HLLS readings ($R_{HLLDEXP}$ and $R_{HLLSEXP}$) in the anisotropic shale. The rearranged equations are

$$R_{HLLDEXP} \approx R_{HRD} \ \{1.00 + 0.11 \ln (R_v/R_h)\} \qquad (10)$$

$$R_{HLLSEXP} \approx R_{HRD} \ \{1.00 + 0.16 \ln (R_v/R_h)\} \qquad (11)$$

The anisotropy of Figure 6c is obtained from DFL and HRI resistivity data. The computed HLLS resistivity $R_{HLLSEXP}$ is close to the actual HLLS log resistivity R_{HLLS}, as shown in Figure 7b. The computed HLLD resistivity $R_{HLLDEXP}$ is also close to the actual HLLD resistivity R_{HLLD} below 1,550 feet. However, the actual R_{HLLD} resistivity is larger than $R_{HLLDEXP}$ above that depth. This difference is likely the result of a high-resistivity, shoulder-bed effect on the deep-reading HLLD from a resistive formation above 1,528 feet.

We also computed the anisotropy from HEDL and HRI resistivity data with Equations 10 and 11. Figure 7c shows the results. The anisotropy computed from the difference between HLLS and HRD is consistent with that from the difference between DFL and HRD. The anisotropy from HLLD agrees reasonably for the depth below 1,550 feet but is larger than that from DFL above that depth, again indicating a high-resistivity, shoulder-bed effect on the deep-reading HLLD.

An attempt to estimate anisotropy from a comparison of raw HLLD and HLLS data was not satisfactory. The anisotropy estimate was too low ($R_v/R_h = 2$ instead of 4), and the horizontal resistivity estimate was too high ($R_h = 15$ ohm·m instead of 14 ohm·m). The horizontal resistivity estimate improved if the HLLD resistivity was lowered by 3 to 5% to account for the possible shoulder-bed effect.

CONCLUSION

Induction resistivity devices read the horizontal resistivity in vertical holes. The vertical resistivity

affects induction log responses only in highly deviated boreholes or in formations with high relative dip angles. On the other hand, formation resistivity anisotropy affects laterolog responses in vertical holes. The effect is manifested as different borehole corrections for different formation anisotropies. The effects are tool dependent. The effect is larger for shallowly focused laterologs, such as DFL and LLS, than for deeply focused LLD.

Analyzing borehole corrections for different formation anisotropies shows that the effect has a nearly logarithmic dependence on anisotropy. The difference between induction log and laterolog resistivities can be used to identify and quantify the formation anisotropy if other environmental effects are negligible or have been corrected. Similarly, though less practical, the difference between the LLDs and LLSs can be used to determine anisotropy. We propose a method to estimate anisotropy with empirical equations that relate anisotropy to the difference between two types of resistivity data. The method is valid for a wide range of formation resistivities.

We applied the method to actual field data from a vertical hole in a thick shale formation without invasion. From the DFL and HRI resistivity data, the shale anisotropy was estimated to be 3.5 to 4. The HEDL data are consistent with the anisotropy value.

The HRI is routinely logged with DFL. In shale formations and in laminated formations with negligible invasion, the difference between the HRI and DFL resistivity data can be used to determine the formation anisotropy in vertical holes. In invaded formations, both induction logs and laterologs should have similar depths of investigation so that the present method is meaningful.

NOMENCLATURE

- σ = conductivity
- θ = deviation angle or dip angle
- ϕ = porosity
- A = diameter
- b = tool coefficient for anisotropy calculation
- H = formation thickness
- R = resistivity

Subscripts

- a = apparent
- bh = borehole
- c = corrected
- EXP = expected
- h = horizontal
- v = vertical

Mnemonics

- DFL = digitally focused log
- HEDL = hostile-environment dual laterolog
- HLLD = hostile-environment laterolog, deep
- HLLS = hostile-environment laterolog, shallow
- HRD = high-resolution induction, deep
- HRM = high-resolution induction, medium
- HRI = high-resolution induction
- LLD = laterolog, deep
- LLS = laterolog, shallow

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ABOUT THE AUTHOR

Teruhiko (Terry) Hagiwara received a Bachelor of Science degree from Tokyo University, Tokyo, and doctorate in physics from the State University of New York at Stony Brook. He joined the electromagnetic group of Halliburton's research department in Houston, Texas, in 1993, and moved to Halliburton's reservoir applications development group in 1999. Previously, he worked at the Bellaire Research Center of Shell Development Company in Houston. He may be reached at terry.hagiwara@halliburton.com.

APPENDIX

Importance of Thinly Laminated Formations. Resistivity logs are commonly used to identify hydrocarbon-bearing formations by their high resistivity readings. However, low-resistivity formations exist that are hydrocarbon productive. Many are thinly laminated formations composed of thin hydrocarbon-bearing sand laminae and thin, nonproductive shale laminae. Because of the thin lamination, resistivity logs cannot resolve the resistivity of each individual lamina. Instead, resistivity logs read an average resistivity of the sand and shale sequence, which is less than the resistivity of the sands.

Because of this low resistivity reading, hydrocarbon saturation is greatly underestimated for thinly laminated formations and may be overlooked as nonproductive. Suppose that a laminated formation is composed of 50% sand and 50% shale. The ratio of net sand thickness to gross formation thickness (N/G) is thus 0.50. If formation porosity is ϕ, formation thickness is H, and the sand laminae are saturated at 30% with brine, then the reserve estimate for the formation is given by

$$(1 - S_w)\cdot\phi\cdot H\cdot(N/G) = (1 - 0.30)\cdot\phi\cdot H\cdot(0.50) = 0.35\cdot\phi\cdot H \quad \text{(A-1)}$$

Note that, if the sand porosity is about 30% and the brine resistivity is about 0.1 ohm·m, then Archie's equation with a = m = n = 1 yields a sand lamina resistivity of about 10 ohm·m.

For this same formation, suppose that shale lamina resistivity is 1 ohm·m. Then, the average (parallel) resistivity of the formation that the log would measure is 1.8 ohm·m. If the whole formation is regarded as a 30% porosity sandstone formation, then a 1.8-ohm·m resistivity suggests a 78% water saturation. The reserve estimate is then $0.22\cdot\phi\cdot H$, which is about 40% lower than the true value.

Interpretation of Thinly Laminated Formations. If a formation is known to be a thinly laminated sequence, then a correct, higher resistivity can be obtained for the sand laminae from the low log resistivity. In turn, a correct, higher hydrocarbon saturation can be estimated.

Consider the previous example. If the formation is known to be laminated with a 50% N/G ratio and a 1-ohm·m shale-lamina resistivity, then a 1.8- ohm·m log resistivity can be used to estimate a sand-lamina resistivity of about 10 ohm·m. Then, the true reserve estimate is calculated as $0.35\cdot\phi\cdot H$, which is more than 60% larger than $0.22\cdot\phi\cdot H$, the estimate one would obtain if the formation were not known to be laminated.

Detection of a Thinly Laminated Formation. Knowing whether a low-resistivity formation is laminated is important. However, few methods exist to find this information. If cores are taken from the formation, visual inspection can identify lamination. Without cores, lamination can be identified with high-resolution downhole imaging tools, such as electrical micro-imaging and circumferential acoustic scanning devices. A dipmeter and other high-resolution logging tools may be also used as long as the tool can delineate laminae.

Does any other method exist to determine lamination, especially by resistivity logs alone? The key is to recognize that a laminated formation appears to induction and other electric logs as a homogeneous and anisotropic formation. Hence, a formation of significant anisotropy may well be a laminated sequence because most rock formations are known to be isotropic or nearly so.

Detection of Anisotropy in Highly Deviated Holes. Can anisotropy be measured by resistivity logs? To measure anisotropy, at least two resistivity measurements must be made, and both the horizontal and vertical resistivities must be determined. Two methods have been proposed to estimate anisotropy with resistivity logs: (1) the use of an induction log or electric log in more than one deviated hole and (2) the use of a high-frequency induction tool in a highly deviated hole.

Induction or Electric Log in More Than One Deviated Borehole. In a deviated borehole, an induction log reads

$$\sigma_{Log} = \sigma_h \sqrt{\cos^2\theta + \frac{R_h}{R_v}\sin^2\theta} \quad \text{(A-2)}$$

where θ is the deviation angle (or dip angle for a dipping formation), σ_h is the horizontal formation conductivity, and R_v/R_h is the formation anisotropy. Therefore, if a formation is penetrated by more than one borehole with a different deviation angle, anisotropy ($R_v/R_h \neq 1$) can be estimated from resistivity and conductivity data at these boreholes. However, this method requires at least two boreholes with largely different deviation angles and assumes that the formation remains uniform between the two wells.

High-Frequency Induction Tool, Such as a Measurement-While-Drilling (MWD) Tool Operating at 2 MHz, in a Highly Deviated Borehole. MWD induction tools operating at a 2-MHz frequency derive formation resistivity in two ways: by phase difference and by attenuation. The two respond differently to invasion, shoulder beds, formation dielectric constant, and formation anisotropy. In a thick formation with shallow or negligible invasion, the difference between the phase- and attenuation-derived resistivities may be a result of formation anisotropy. Some 2-MHz induction tools use more than one transmitter-receiver spacing. When these tools are used, the effect of anisotropy is realized as the difference between the phase- or attenuation-derived resistivities from the different spacings after the invasion effect is eliminated. The anisotropy effect—the difference between the two resistivities—is more prominent at higher deviation angles. Thus, this method does not apply to a vertical or low-deviation borehole.

Table 1—Tool Coefficient for Anisotropy Calculations

A_{bh}	8 inches	10 inches	12 inches	14 inches	16 inches
b_{LLD}	0.10	0.10	0.11	0.11	0.11
b_{LLS}	0.17	0.18	0.19	0.20	0.21
b_{DFL}	0.17	0.18	0.19	0.19	0.20

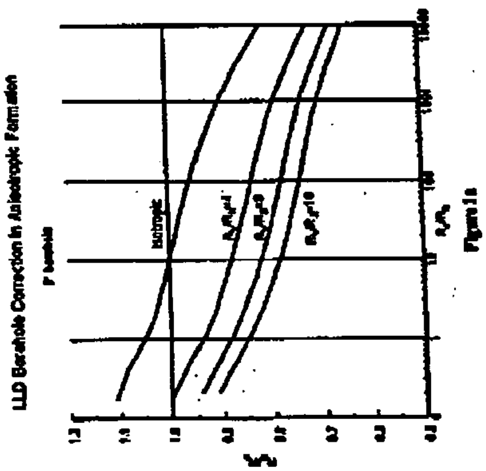

Figure 1a

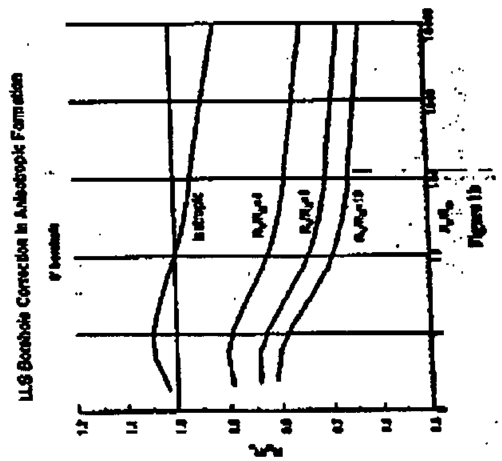

Figure 1b

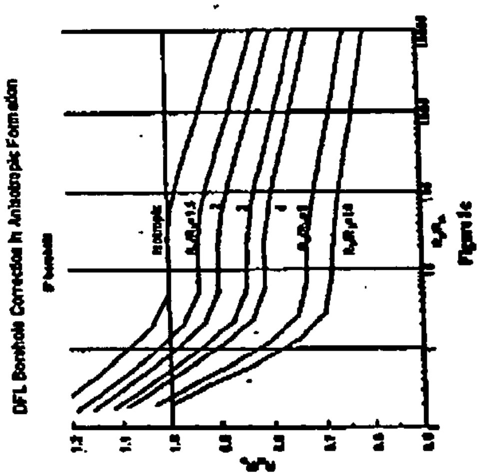

Figure 1c

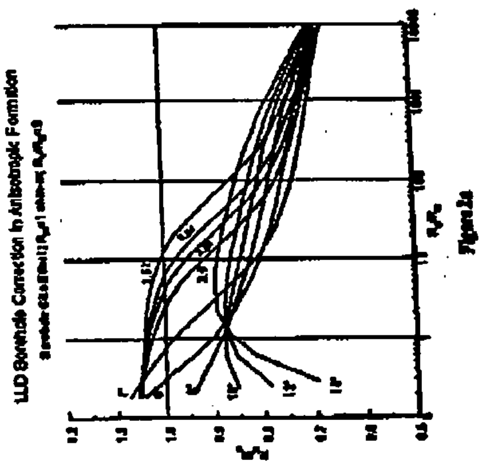

Figure 2a

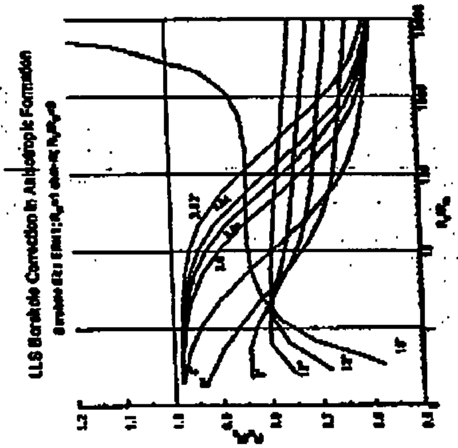

Figure 2b

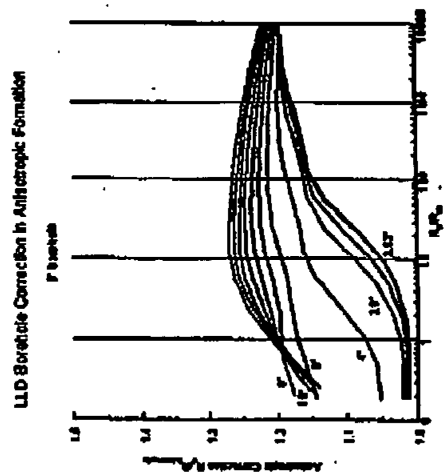

Figure 3a

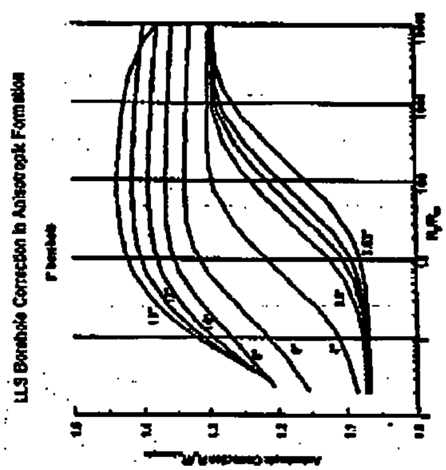

Figure 3b

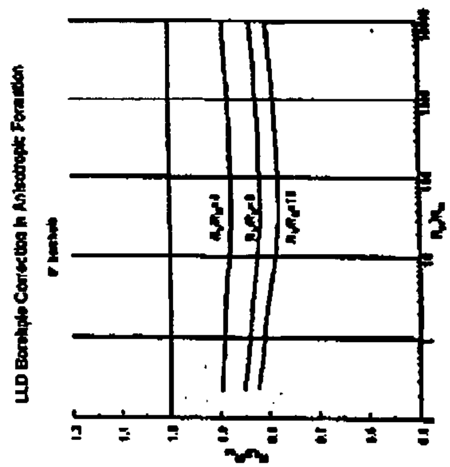

Figure 4a

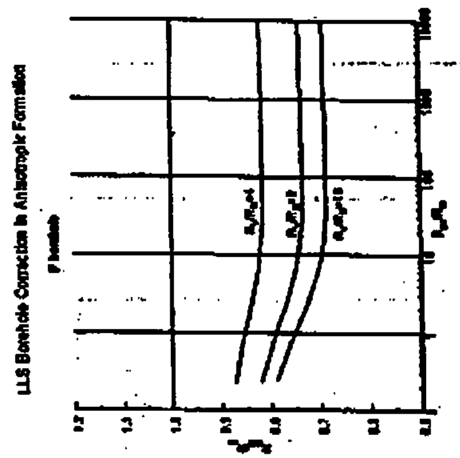

Figure 4b

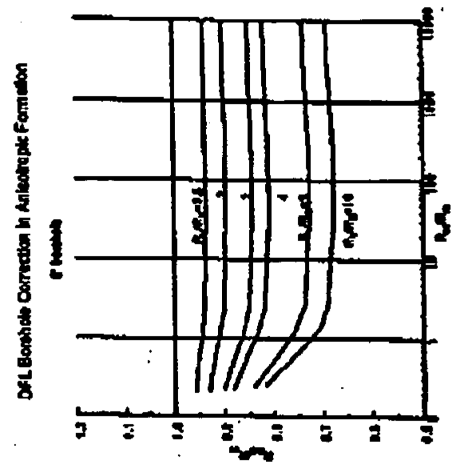

Figure 4c

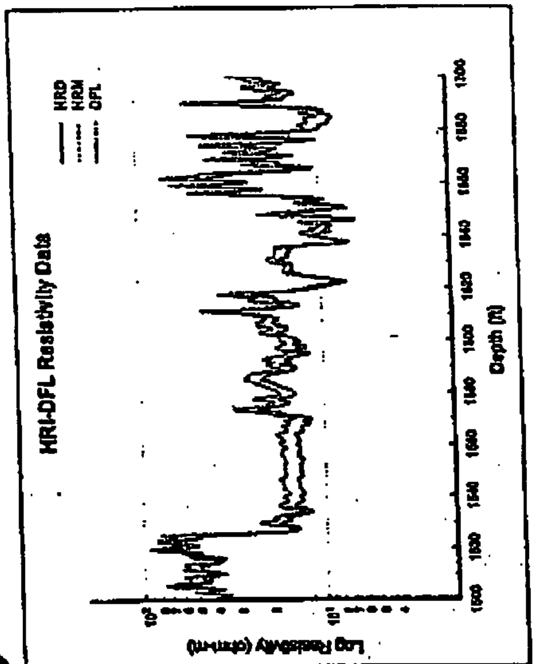

Figure 6a

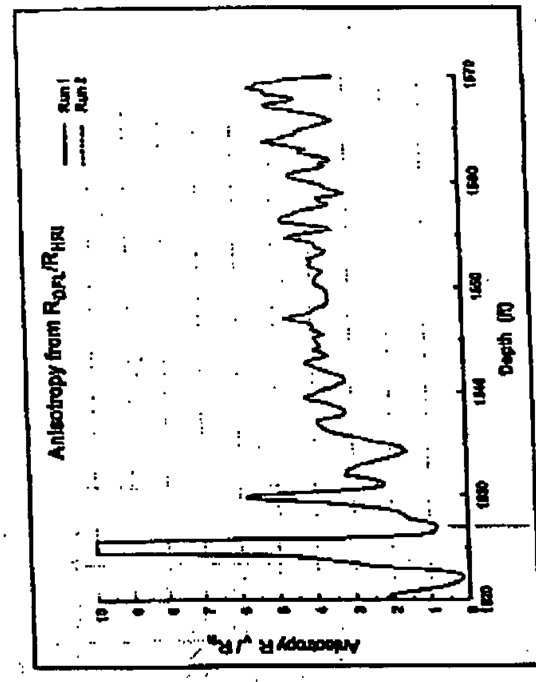

Figure 6c

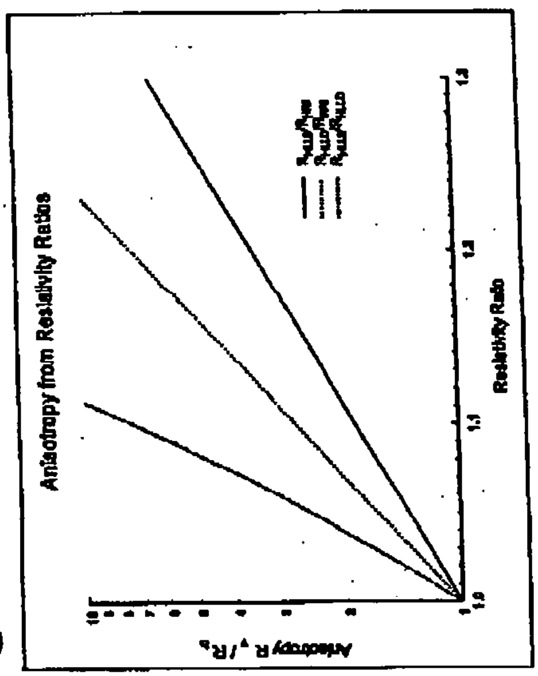

Figure 5

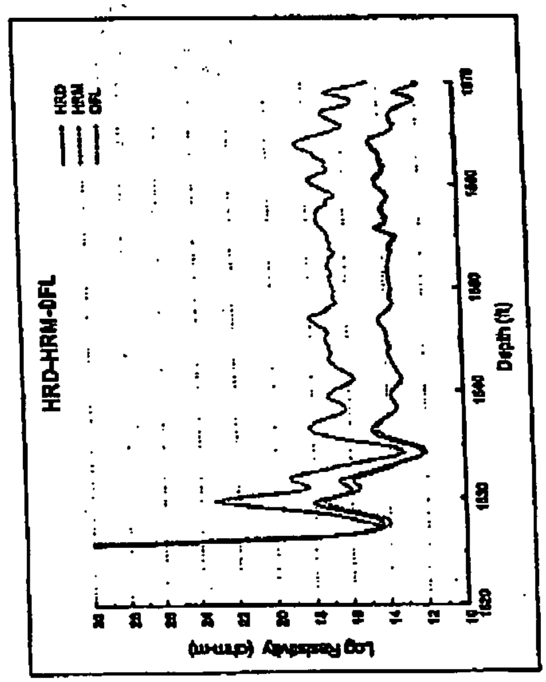

Figure 6b

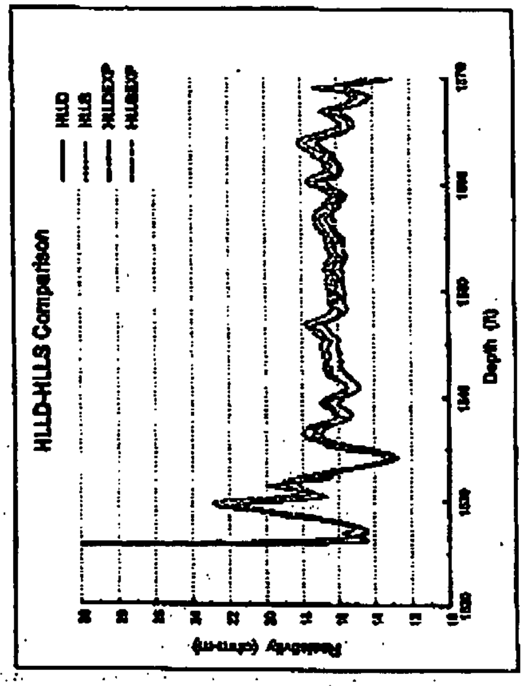

Figure 7b

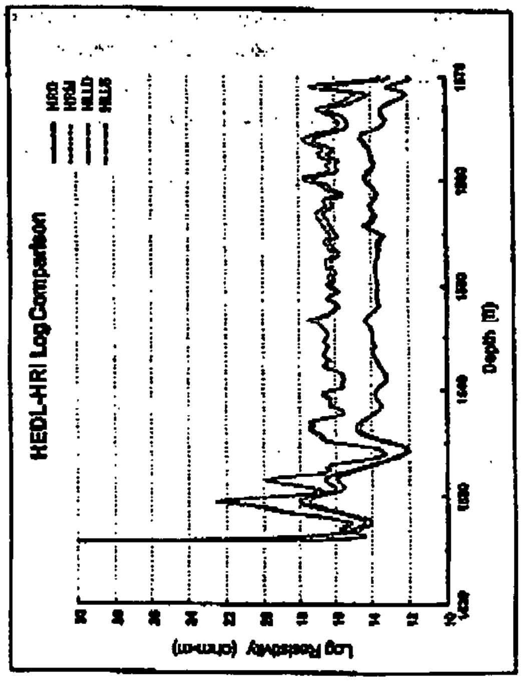

Figure 7a

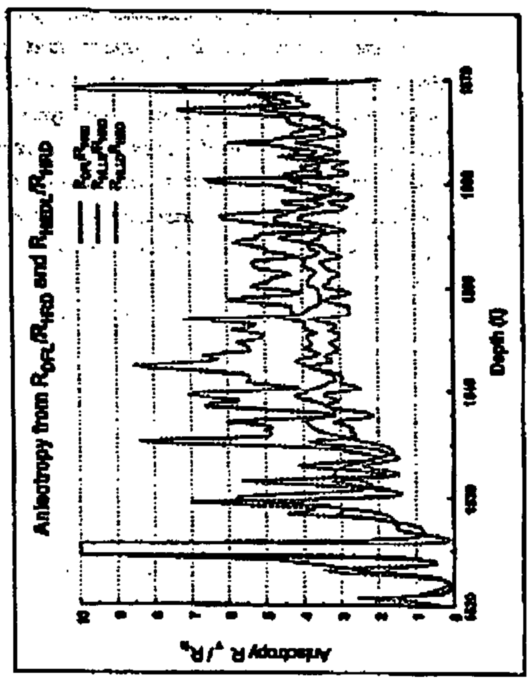

Figure 7c